DEVELOPMENT OF AN INTENSE SURFACE DISCHARGE PUMPED VACUUM ULTRAVIOLET LAMP

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Abstract

A large area (15 cm x 15 cm) uniform vacuum ultraviolet light source employing surface discharge pumping scheme has been developed for semiconductor processing applications. A low inductance pulsed power circuit for initiating the large area uniform surface discharge was constructed. The total stored energy in the capacitors (4.2 μF) is 1.9 kJ when charged to 30 kV. A current pulse of 1.5 μs with a peak of 210 kA is deposited to the discharge load from the three capacitor modules. The uniformity of the light over the large area surface discharge is 5% on the surface from visible light measurement when alumina is used as a discharge plate material.

1. Introduction

Vacuum ultraviolet (VUV) light sources are attractive for optical material processing because high photon energy makes it capable of photo-chemical bond breaking. This property plus the relatively short pulse nature of the source opens a variety of semiconductor and flat panel display processing applications. These include applications from photo-resist ashing to activation of electro-luminescent phosphors.

We designed a light source by setting the application target to ashing of photoresist [1] in the semiconductor lithography process. In the near future of the semiconductor processing technology where eight inch wafers and a quarter micrometer structures become common, rf or microwave oxygen plasma dry etching processing to create atomic oxygen to react away the hardened photoresist is considered no longer viable due to the statistical rate of damage from bombardment of ions on the substructures once the photoresist is removed. In an effort to eliminate the ion induced damage, a group at the Colorado State University (CSU) has developed a low pressure, electron beam initiated, VUV source that is used to dissociate molecular oxygen [2]. They produced an ashing rate comparable to oxygen discharge reactors. A surface discharge [3] or a formed ferrite [4] light source can create intense UV light at a plane far from the wafer; thus there will be no ions in the region of the wafer structures similar to the CSU work but at an intensity even at 1 Hz pulse rate of approximately 1000 times greater. Therefore, tremendous improvement in photoresist removal rate seems possible. Such a source, however, must be extremely clean and the whole reactor must not contain any fluoro- or chloro-carbon materials; and such a source must be uniform (to better than 5%) so that the photoresist removal can proceed uniformly across the whole wafer such that the substructures is exposed minimally to possibility of damage due to the intense UV light source.

For the purpose of quick removal of photoresist in production lines, the light source must have a high output power density and a large emission area. For developing such a VUV light source, we employed a surface discharge pumping scheme and designed a single shot machine to examine the ability of this scheme. This scheme (as used in chemical laser applications) has already shown outstanding performances in photon flux generation in the 240 to 340 nm region. Energy in this band as high as 2 J/cm^2 has been achieved at a wall-plug efficiency of 5% [3].

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUL 1995	**N/A**	**-**

4. TITLE AND SUBTITLE	
Development Of An Intense Surface Discharge Pumped Vacuum Ultraviolet Lamp Pegasus	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Chemical Science and Technology Division Advanced Optical System Group, CST-2 Los Alamos National Laboratory Mail Stop E535, E543a) Los Alamos, NM 87545**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
A large area (15 em x 15 em) uniform vacuum ultraviolet light source employing surface discharge pumping scheme has been developed for semiconductor processing applications. A low inductance pulsed power circuit for initiating the large area uniform surface discharge was constructed. The total stored energy in the capacitors (4.21-LF) is 1.9 kJ when charged to 30 kV. A current pulse of 1.5 !lS with a peak of 210 kA is deposited to the discharge load from the three capacitor modules. The uniformity of the light over the large area surface discharge is 5% on the surface from visible light measurement when alumina is used as a discharge plate material.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**6**	

This paper describes the development of an intense surface discharge pumped VUV lamp. The design of low inductance pulse power circuits and a surface discharge light source, and experimental results are discussed.

2. Design

2.1 Design Concept

We designed a light source by setting the application target to the ashing of photoresist in the semiconductor lithography process. Although the present trend is toward 8" (20 cm) wafer, we started from a 6" (15 cm) x 6" (15 cm) = 225 cm^2 emission area light source. This is because uniform discharge can be obtained with lower voltage of 40 kV, which makes the design of the pulsed power part easier and allows us to use commercial alumina bushing as a voltage stand-off in a discharge chamber. The use of alumina ceramics bushing eliminates organic material for insulators in the chamber, and, thus, resulting in an extremely clean system.

2.2 Excitation Circuit Design

A high peak power density of several megawatts per cm^2 is required to generate VUV light efficiently. A large energy of a few kilojoules is to be deposited to the surface discharge to form an intense, large area (225 cm^2) VUV emission.

Figure 1 is the electrical circuit of the exciter designed. The pulse power circuit is composed of three independent charge transfer circuits to reduce the peak current per triggered spark gap (Maxwell Model 40044, 50 kV, 50 kA). All the spark gap switches are triggered with a single trigger generator. The main capacitor of each circuit is 1.4 μF, which consists of two parallel low inductance capacitors (Maxwell Laboratory, Model 31161, 0.7 μF, 17-25 nH, 50 kV, 25 kA). A DC power supply (40 kV, 60 mA) charges the main capacitors through a charging resistor and isolation resistors. The main capacitors are charged negatively to make uniform surface discharge initiation easier.

For the impedance matching between a low surface discharge resistance and the excitation circuit, the output inductance of the excitation is designed to be as low as possible. By placing the circuits in transformer oil, the parallel conductor plates between the main capacitor and the discharge electrodes are set as close as possible to minimize the inductance. Stainless steel is used for the main electrodes to minimize erosion by the high density discharge current.

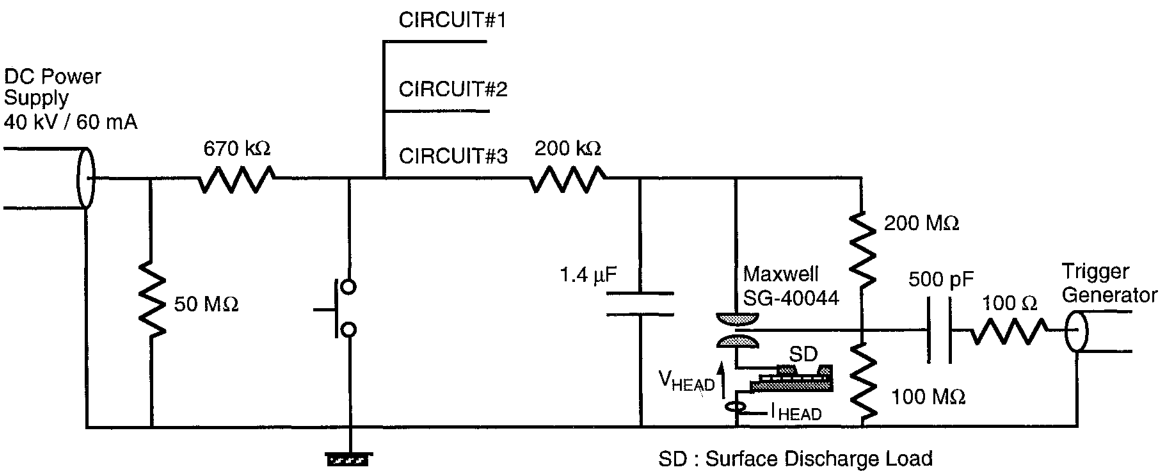

Fig.1 Pulse power circuit diagram for a surface discharge pumped VUV light source.

2.3 Reactor Design

Figure 2 is a picture of the inside of the reactor. The surface discharge condition depends on its discharge capacitance, which consists of a surface discharge plate, a current return plate, and a surface discharge sheath. Increasing the capacitance improves the uniformity of the surface discharge. With the thickness, area, and relative permittivity of a surface discharge plate shown by d, A, and ε, respectively, a capacitance of the surface discharge C_{SD} is given as, approximately,

$$C_{SD} = \varepsilon\varepsilon_0 \frac{A}{d} \quad [F] \qquad (1)$$

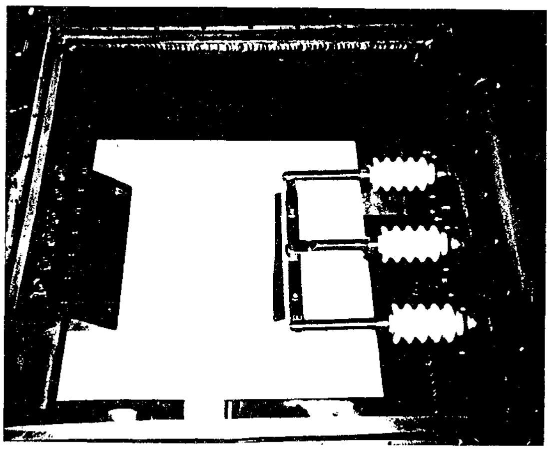

Fig. 2 Picture of the inside of the reactor.

When the material and the size of the discharge are fixed, only the thickness of d can be a variable. The capacitance of the surface discharge is, therefore, inversely proportional to the thickness of the dielectric plate. However, the thickness d should be decided by considering a dielectric strength and the mechanical strength of the materials. Any materials creating free carbon should be avoided for semiconductor applications. Because high density alumina and glass have high dielectric constants of 10 and 7.5, respectively, e.g., 2.07 of Teflon, they are chosen as materials for the plate. To avoid breaking the brittle materials, design of applying only compressive force on the dielectric to hold is used.

Requirements for surface discharge gases are (1) high discharge impedance for a good impedance matching with the discharge circuit for efficient energy transfer from the main capacitors, (2) high efficiency emission in VUV band, (3) materials stability against intense discharge so that these materials do not decompose into undesirable secondary products, and (4) no reaction with the container. For example, noble gases such as He, Ne, Ar, Kr, Xe satisfy the requirements of (3) and (4), the gases and the mixtures of these gases are the candidates. The experiments described use 500 Torr of argon.

3. Experiments and Discussions

3.1 Electrical Circuit

First, performances of the electrical circuit are checked. Typical voltage and current waveforms are in Fig. 3 with an observed visible light waveform detected with a PIN photodiode. The voltage is measured with a combination of a $CuSO_4$ water resistor and a current transformer (Pearson Model 110A) to pick up the current at the water resistor. A P6015 voltage probe (Tektronix) is used to calibrate the voltage probe. The current is picked up with a Rogowski coil. The discharge resistance is calculated from the damping ratio of the current. Here, no change of the discharge resistance is assumed during the period from the first to the second peaks of the current pulse. MICRO-CAP IV (Spectrum) computer software is used to compare the measured waveforms and the calculated to calibrate the current. The discharge resistance including the spark gap switch and the surface discharge is 0.09 Ω at a charging voltage of 30 kV where a 1.5-μm-long (a half cycle of a sine wave) current pulse with a peak of about 70 kA per circuit is measured. The current pulse duration is defined as a duration from the onset to the inversion of current. The total stored energy in the main capacitors is 1.9 kJ. The total inductance of each circuit is 160 nH.

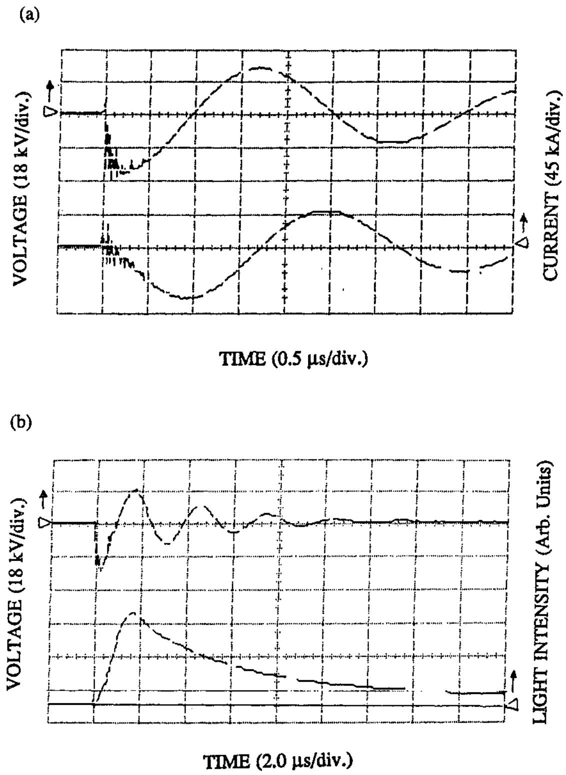

Fig.3 (a) Measured voltage and current at the surface discharge load, (b) measured voltage at the surface discharge and light emitted from the discharge surface.

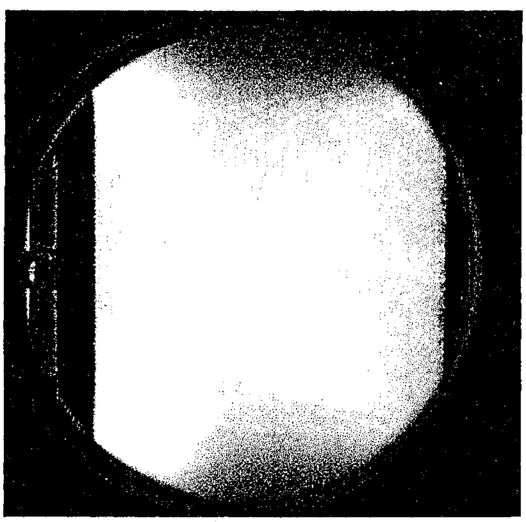

Fig.4 Photo of discharge surface attenuated to bring out fine structure with an alumina plate.

According to Toepler's law, Eq. (2) gives a surface discharge resistance.

$$R_{SD} \cong a \frac{\ell}{V\,w} \qquad (2)$$

a : constant
ℓ : discharge length (A-K) [cm]
V : charging voltage [kV]
w : discharge width [cm].

Equation (2) shows that a surface discharge resistance is proportional to a distance between an anode and a cathode ℓ, and is inversely proportional to a discharge width w and a charging voltage V. The ℓ/w in the right hand side of Eq.(2) shows a geometry of a surface discharge. When applying our parameters of a = 2 [5], w = 15 cm, V = 30 kV, ℓ = 15 cm to Eq.(2), we obtain R_{SD} of 0.067 Ω. From this value, a discharge resistance of the spark gap switch is calculated to be 0.023 Ω. From MICRO-CAP IV simulation, the peak input power density to the surface discharge is estimated to be 4.5 MW/cm^2.

3.2 Surface Discharge

Figure 4 is a photo of the discharge surface attenuated to bring out fine structure. Visible emission from the surface discharge is measured using a CCD camera with a set of neutral density filters and analyzed with Beamcode™ (Big Sky). Figures 5, 6, and 7 show a typical result when a plate of alumina with a thickness of 1/8" (3.175 mm) is used. From Figs.5 and 6, the emission is extremely intense and uniform over a 15 cm x 15 cm emission area. The histogram at Fig.7 shows that the uniformity across the whole surface is 5%. This satisfies the requirement for semiconductor applications. The uniformity is defined as $\Delta I/I_{PEAK}$ where ΔI is the intensity width at half of the maximum pixel count and I_{PEAK} is the intensity at the maximum pixel count. The surface discharge on a 1/8" glass plate shown in Figs.8, 9, and 10 is less uniform. The histogram shows the uniformity of 25%. However, the uniformity improvement is expected on the semiconductor wafer surface plane, which is away from the discharge surface. The difference of the uniformity may attribute to the difference of capacitance of these plates and the surface condition. High density alumina has a higher dielectric constant (10) than the value of typical glass (7.5).

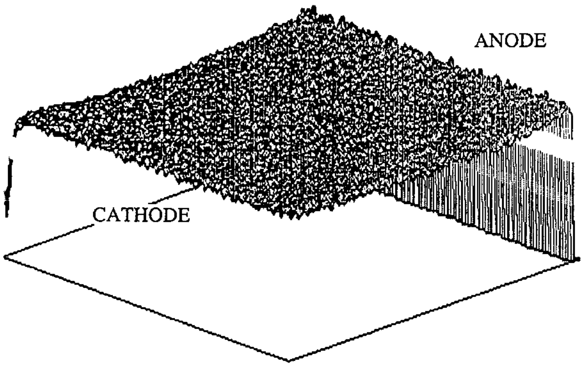

Fig.5 Three dimensional Beamcode display of the surface intensity with an alumina plate.

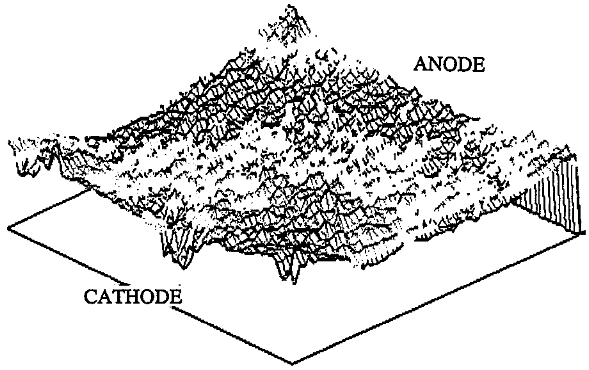

Fig.8 Three dimensional Beamcode display of the surface intensity with a glass plate.

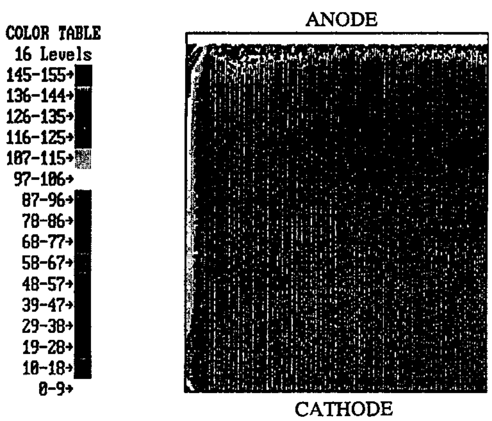

Fig.6 Beamcode display of the surface intensity with an alumina plate.

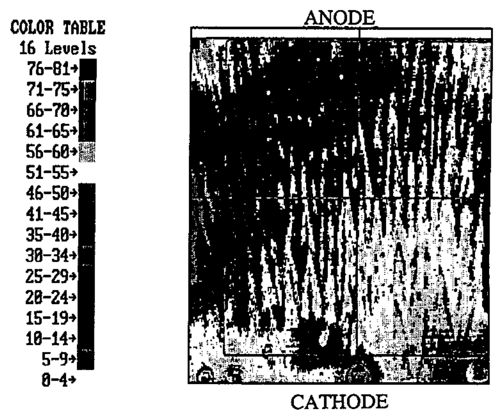

Fig.9 Beamcode display of the surface intensity with a glass plate.

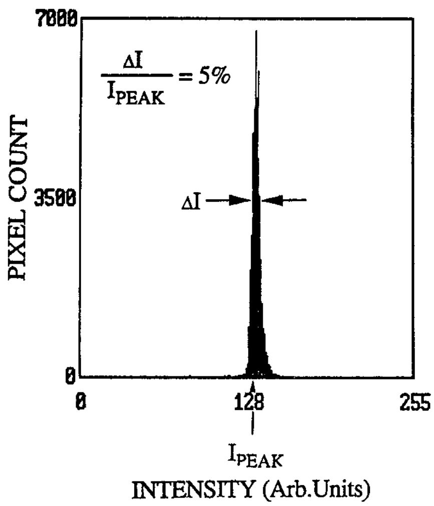

Fig.7 Histogram of the surface intensity variation with an alumina plate.

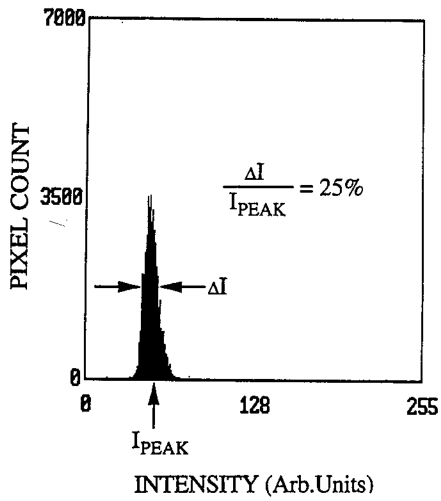

Fig.10 Histogram of the surface intensity variation with a glass plate.

4. Summary

A low inductance pulsed power exciter for initiating an intense surface discharge to emit intense vacuum ultraviolet light has successfully developed. The inductance of each pulse power module is about 160 nH. An operating condition realized is a total stored energy of the main capacitors of 1.9 kJ at the charging voltage of 30 kV. The total peak current of 210 kA is input to the surface discharge load with a current pulse duration of 1.5 μs. A large area (15 cm x 15 cm) uniform (5%) light emission in visible region is measured when an alumina plate of high dielectric constant of 10 is used as a surface discharge dielectric plate.

5. Acknowledgments

The authors would like to thank Gerard P. Quigley, CST-2, Los Alamos National Laboratory for his cooperation.

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